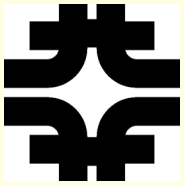
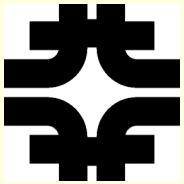


Future Neutrino Experiments

Gina Rameika

Annual Users Meeting

June 6, 2007



Outline

- The Neutrino Landscape
- Fermilab neutrino facilities
- Evolution of the current program
- Planning for the future
  - Long baseline options
  - R & D along the way

The Neutrino Landscape

Three neutrino flavors are related to three neutrino mass states by a mixing matrix :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

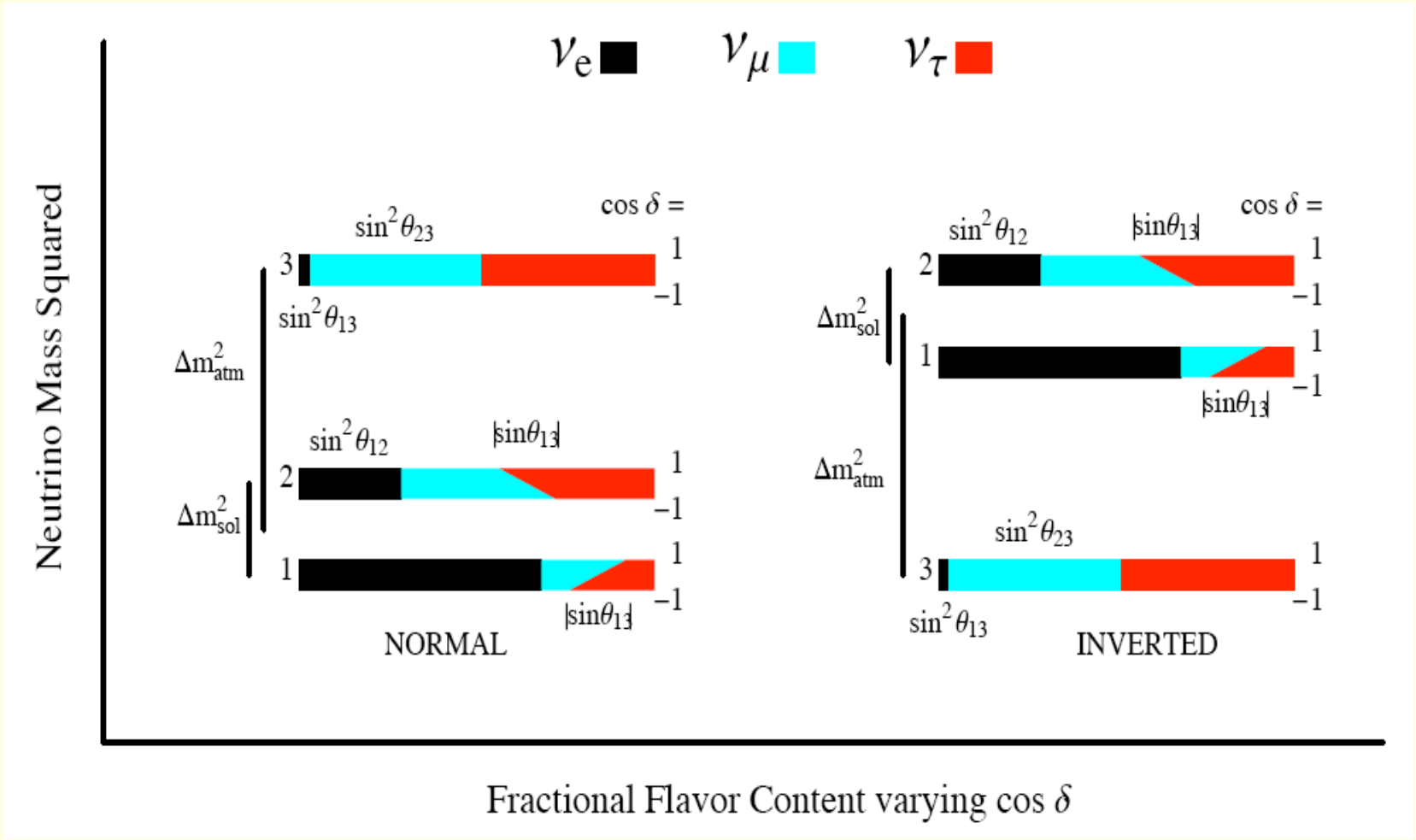
$$\left| \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\rangle = \begin{bmatrix} c\theta_{12} & s\theta_{12} & \\ -s\theta_{12} & c\theta_{12} & \\ & & 1 \end{bmatrix} \begin{bmatrix} c\theta_{13} & & s\theta_{13}e^{-i\delta} \\ & 1 & \\ -s\theta_{13}e^{i\delta} & & c\theta_{13} \end{bmatrix} \begin{bmatrix} 1 & & \\ & c\theta_{23} & s\theta_{23} \\ & -s\theta_{23} & c\theta_{23} \end{bmatrix} \left| \begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix} \right\rangle$$

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2\theta_{12} \ \sin^2(1.27\Delta m^2_{12} L/E)$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2\theta_{23} \ \sin^2(1.27\Delta m^2_{23} L/E)$$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \ \sin^2 2\theta_{13} \ \sin^2(1.27\Delta m^2_{31} L/E)$$

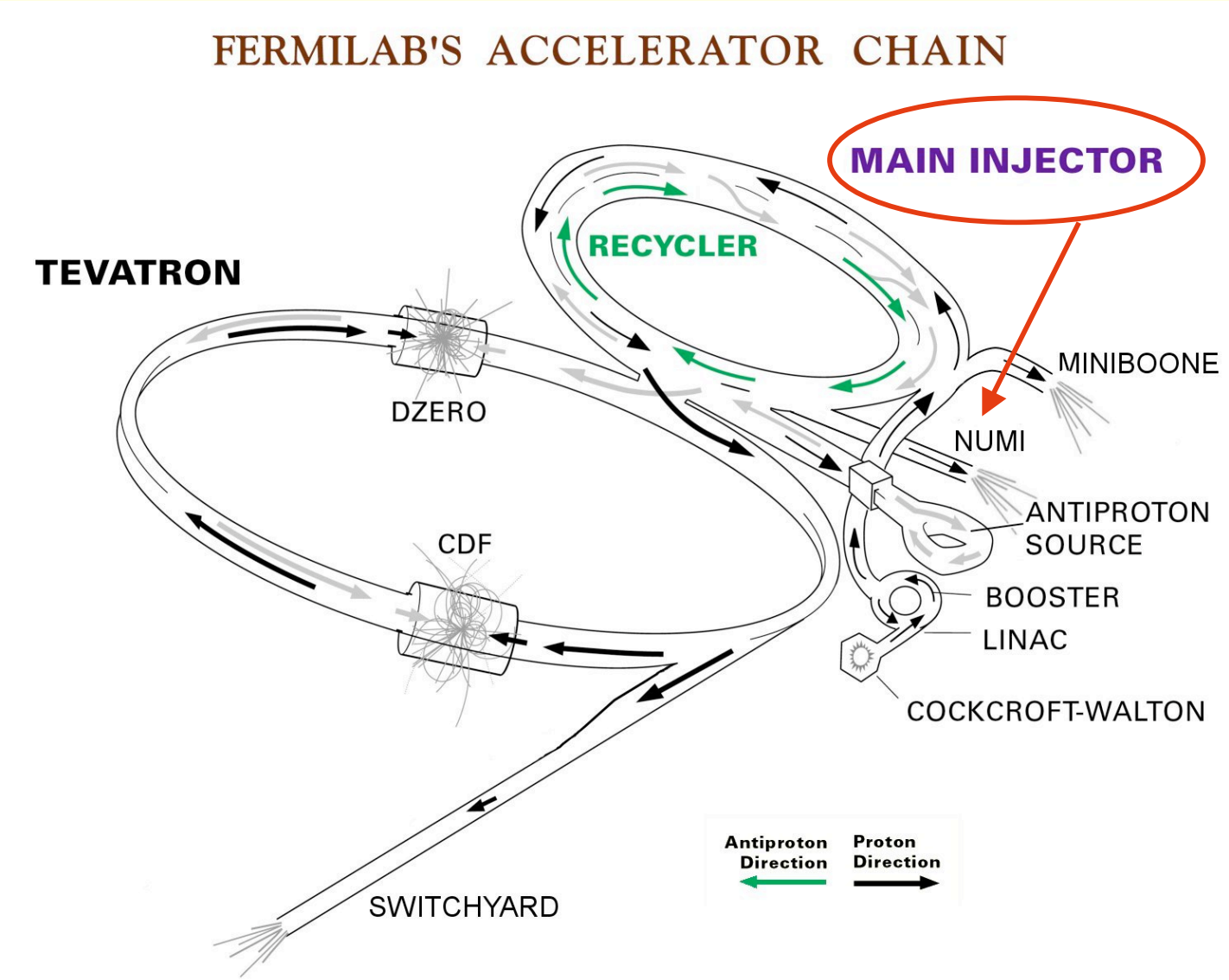
The Neutrino Landscape



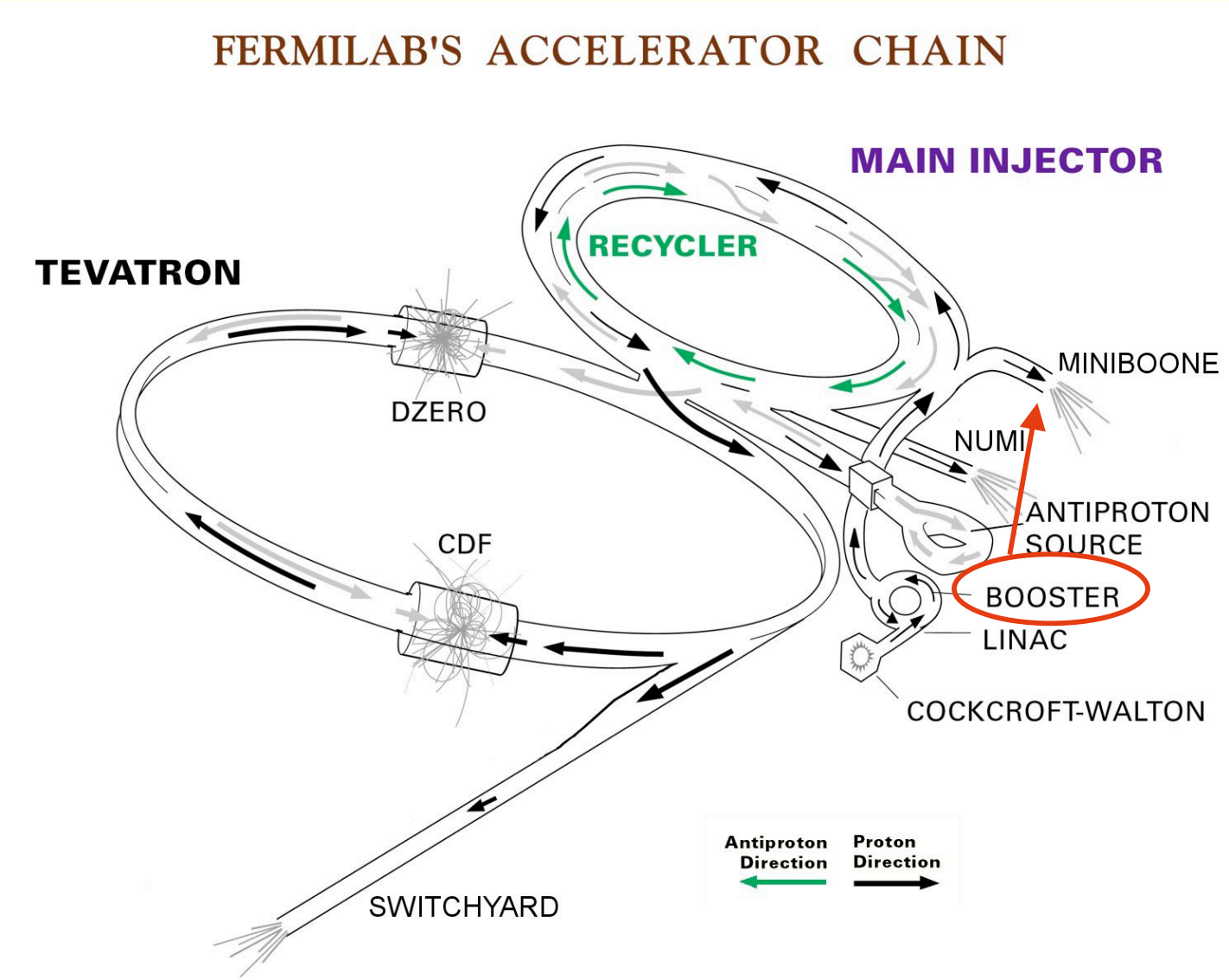
The Neutrino Landscape

- The Open Questions
  - What is the value of $\sin^2 2\theta_{13}$?
    - Just below the current limit? ~0.14
    - Very, very small? < 0.01
    - Exactly zero?
  - Is the mass hierarchy normal or inverted?
    - Most theoretical models for neutrino mass favor the normal hierarchy, but as experimentalists, we must measure it..
  - Is CP violated in the neutrino sector?
    - Can we determine that δ_{CP} is different from 0 or π?
    - Are the anti-neutrino transitions different than the neutrinos?

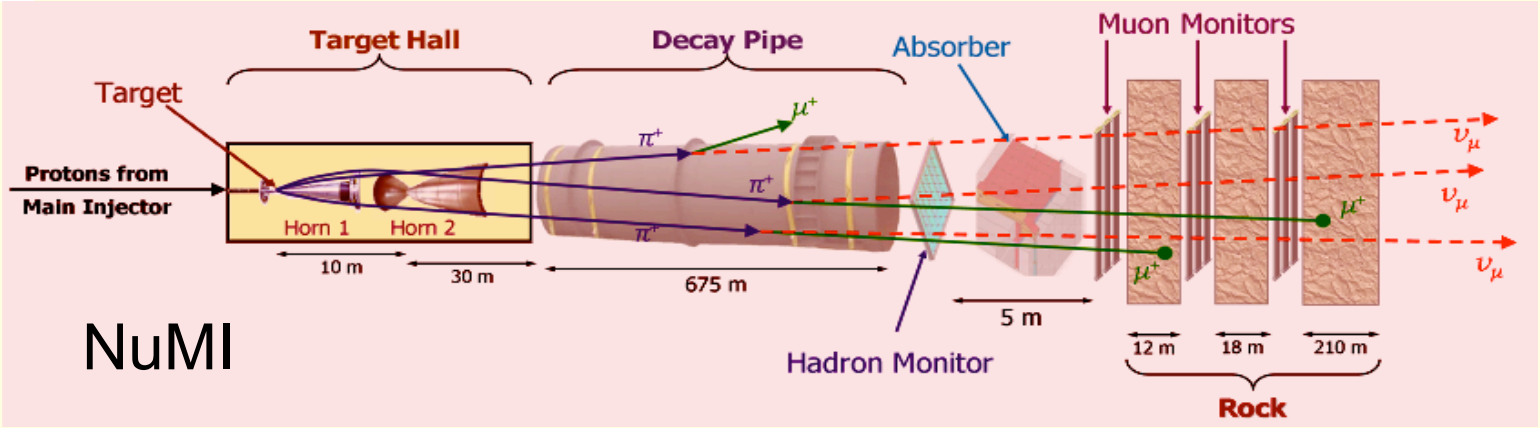
Fermilab neutrino facilities

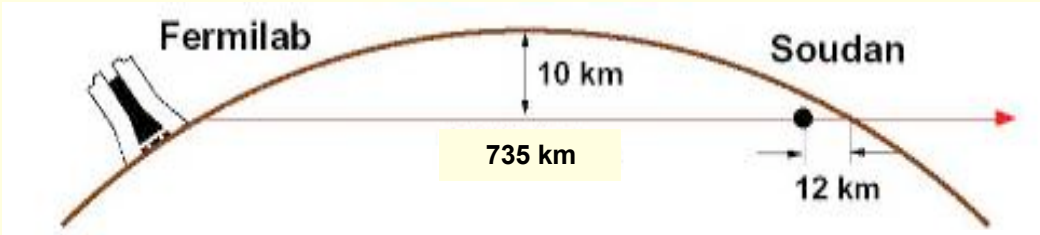


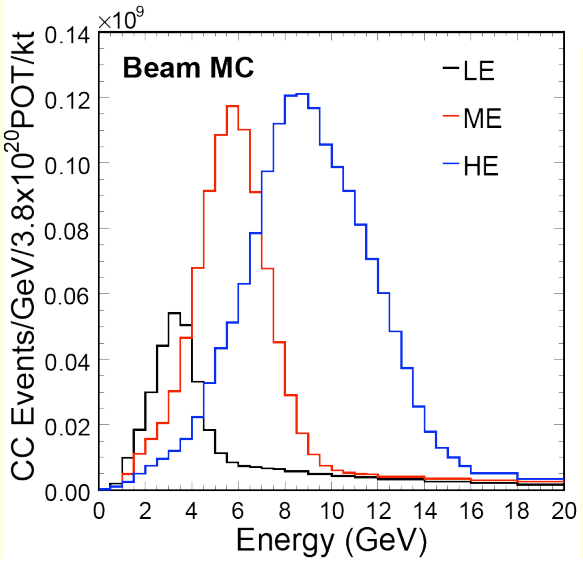
Fermilab neutrino facilities

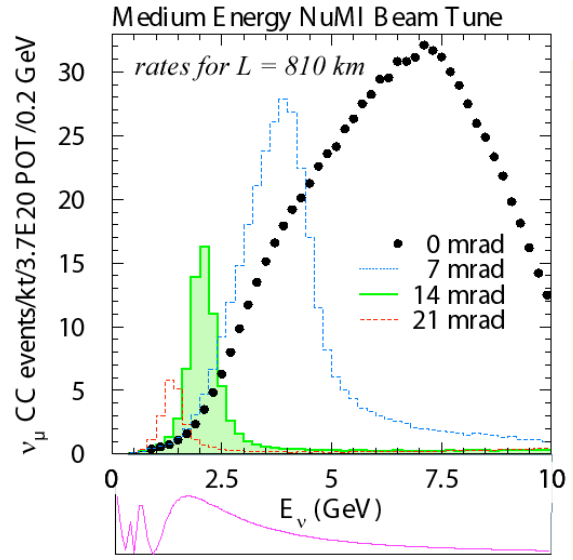


The NuMI Neutrino Beam

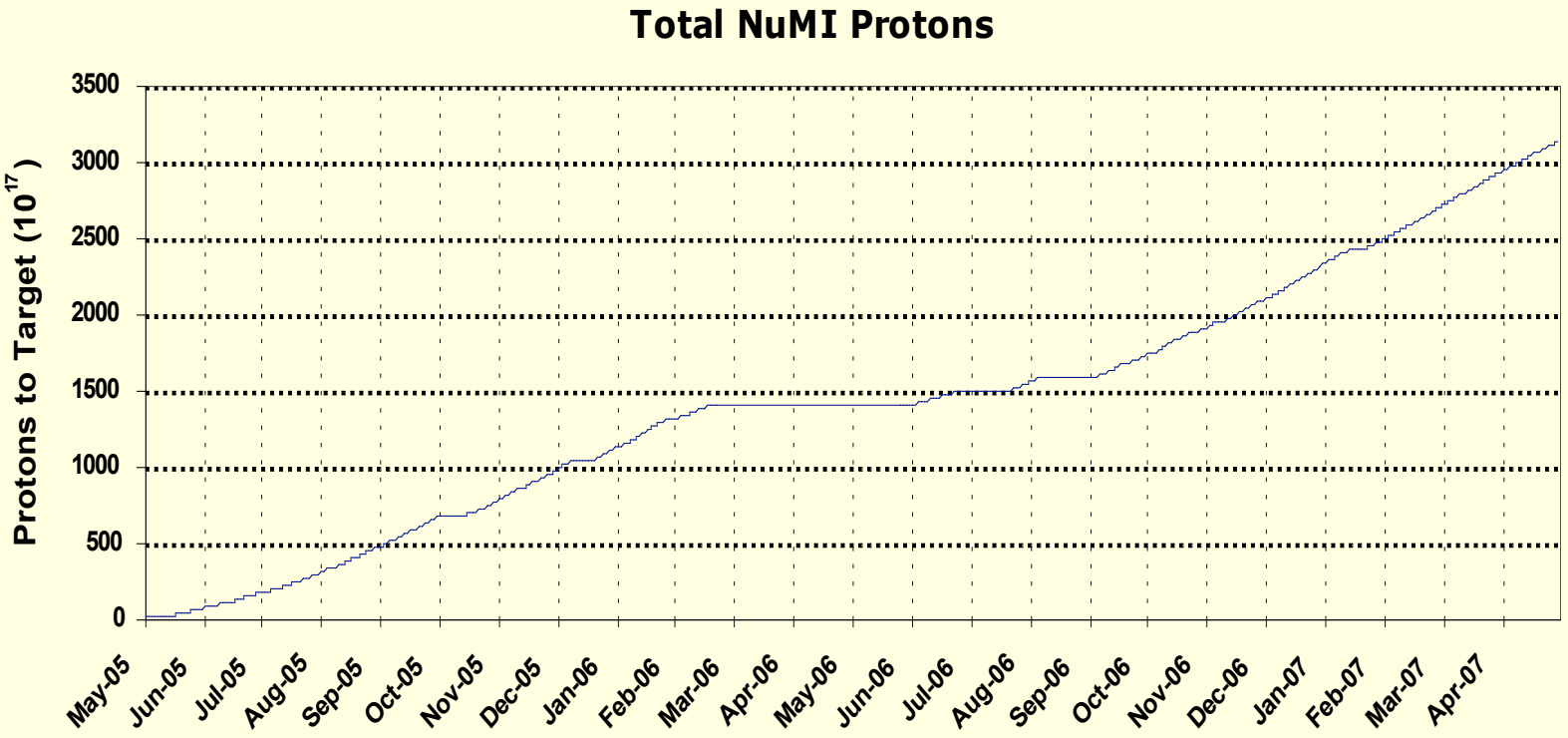








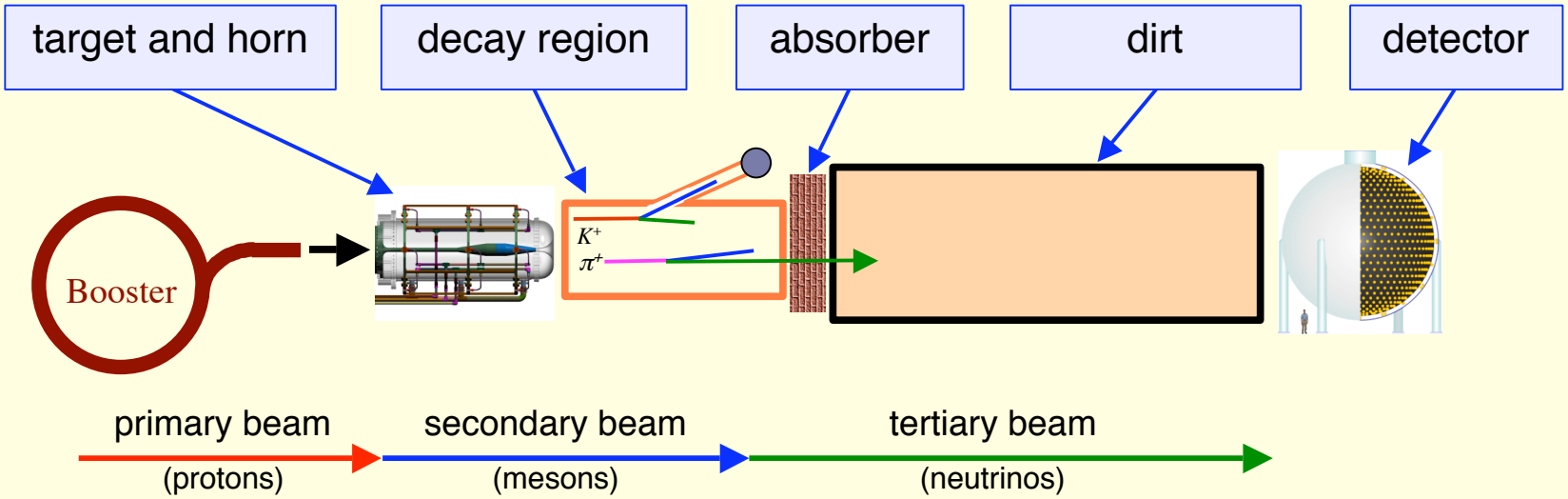
NuMI Operation



>3e20 pot

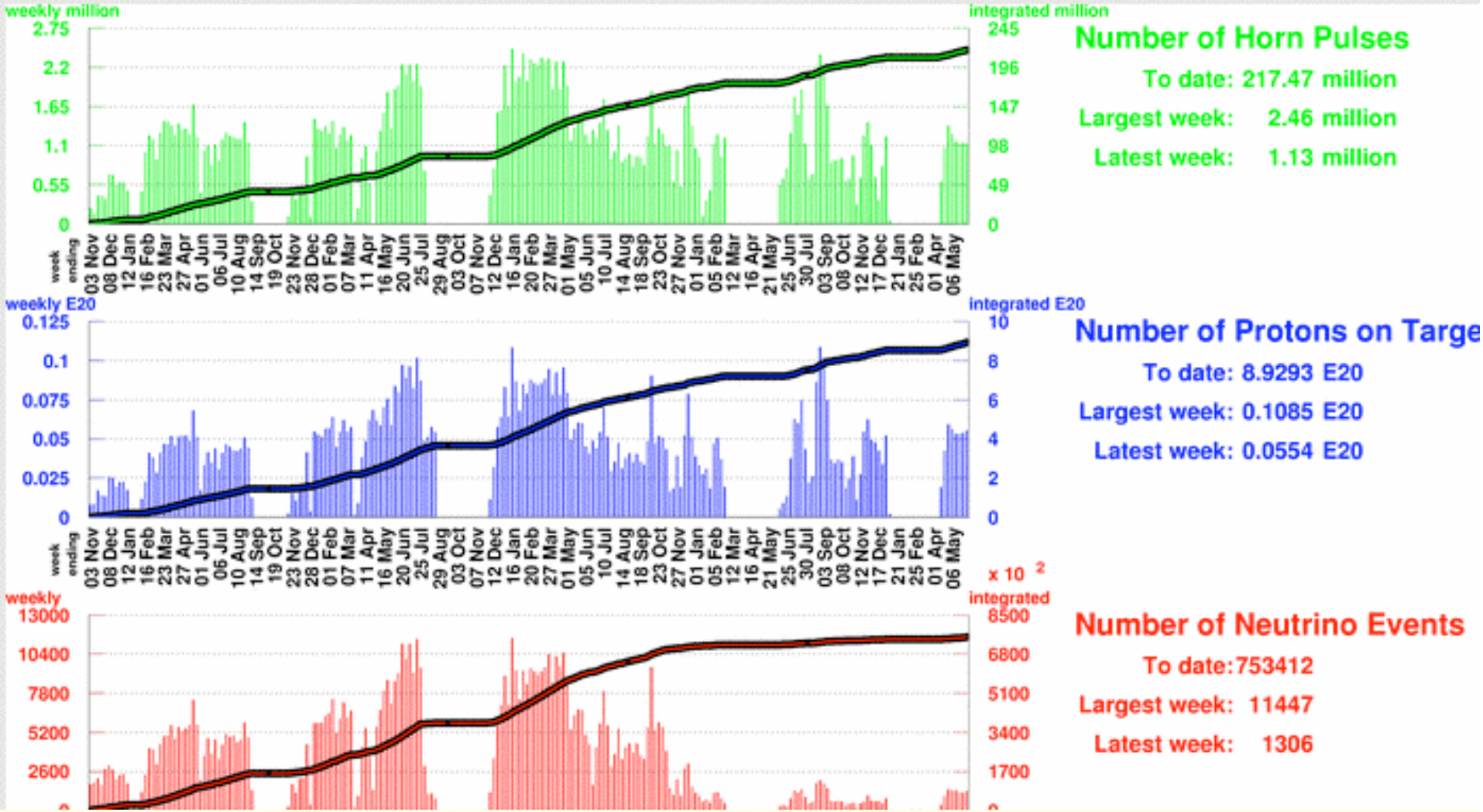
- Recent Achievements:
  - > 4 x 10^{13} protons in a pulse (exceeds design intensity)
  - 325 kW beam power

The Booster Neutrino Beam



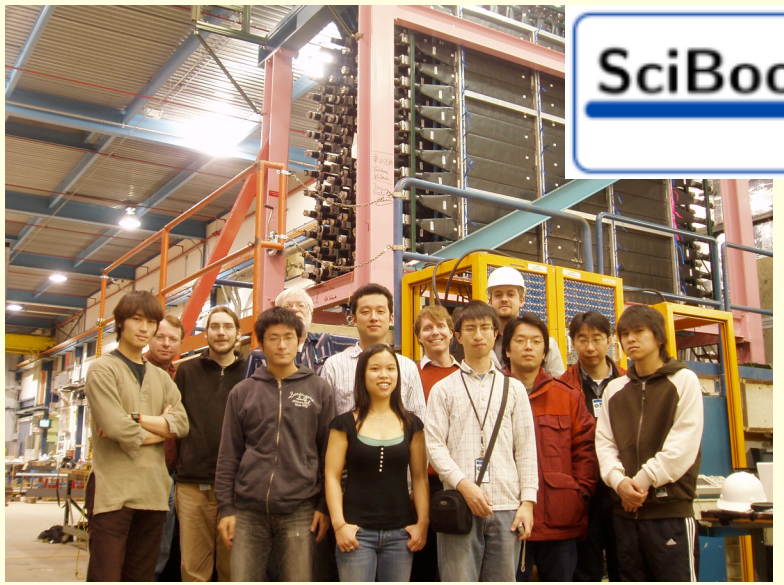
- 4-5e12 ppp; average cycle time 2Hz
  - Last week achieved record average intensity of 4.9e12 ppp
- Operates in neutrino and anti-neutrino mode

The Booster Neutrino Beam



Operation since Nov. 2002

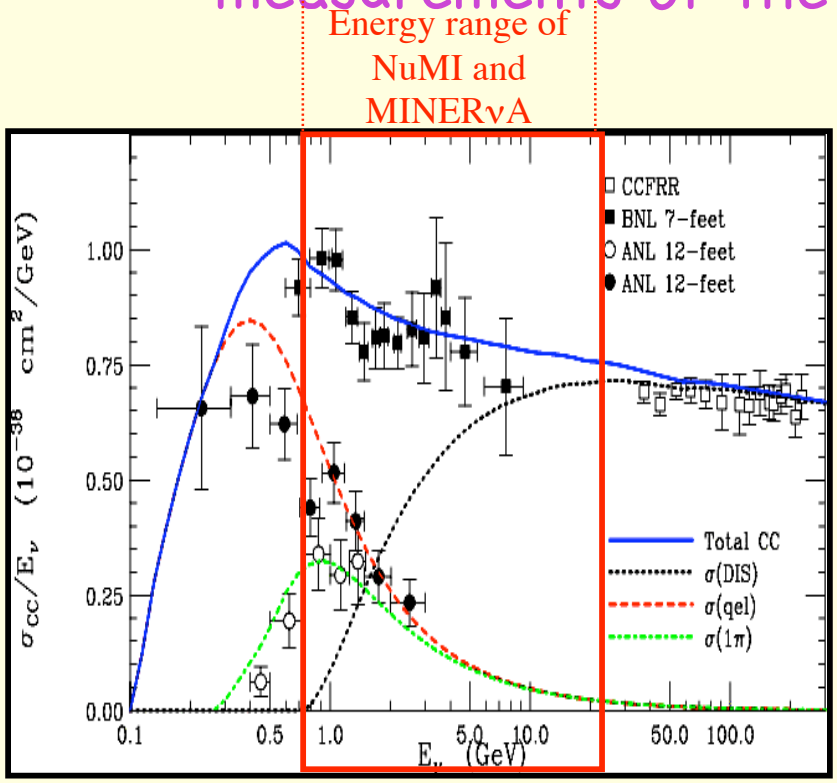
The Nu Experiments

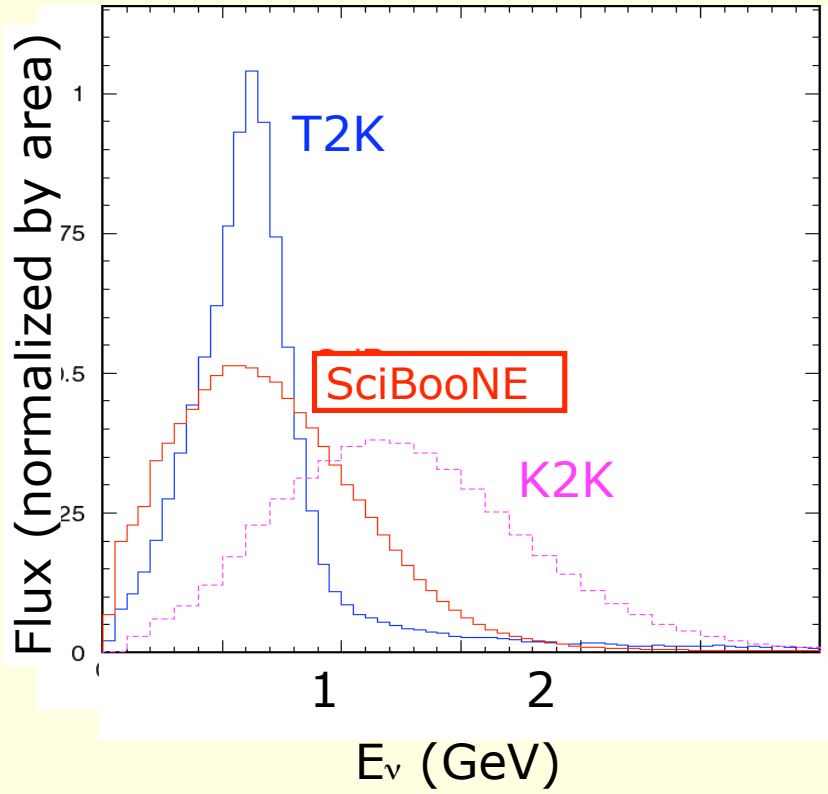


SciBooNE

MINERνA

- The MINERvA and SciBooNE experiments will provide much needed data on neutrino cross sections that will help improve future measurements of the mass-mixing parameters.



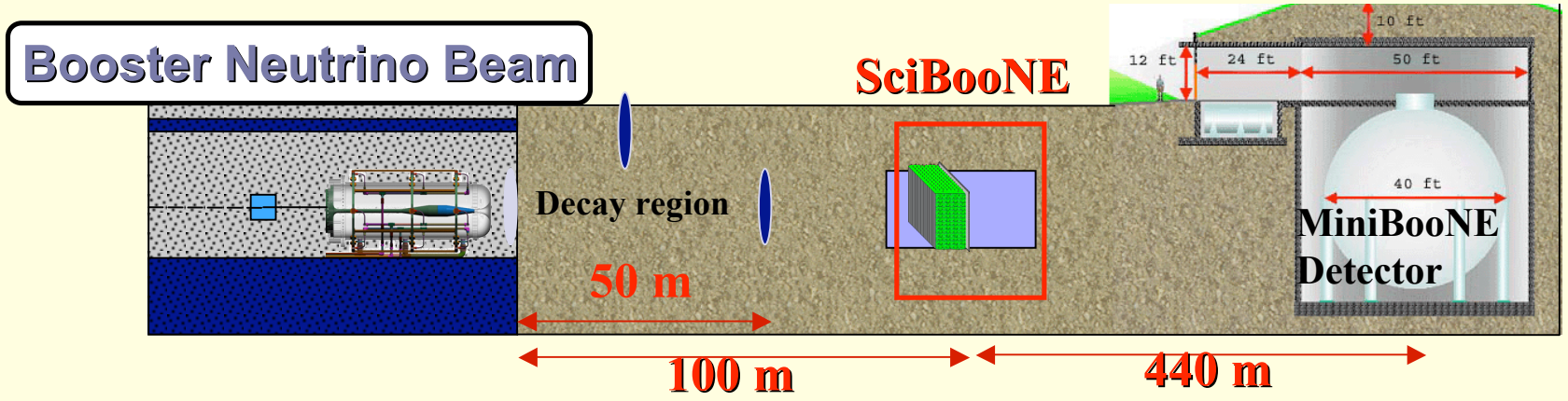


T2K

MINOS

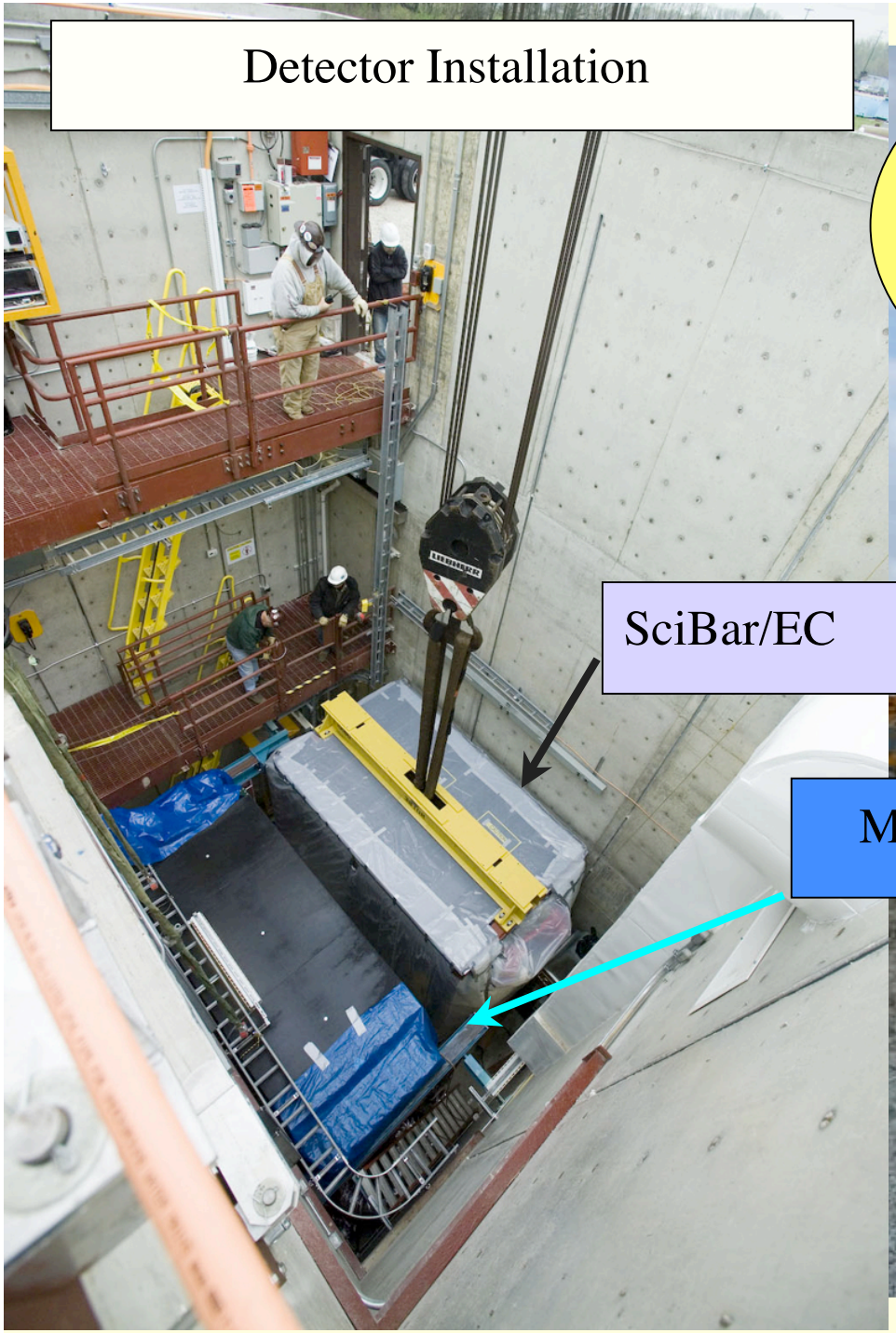
NOvA

Status of SciBooNE



- **2005 Dec - Proposal to FNAL PAC**
- 2006 Mar - First collaboration meeting
- 2006 Apr - Begin work on MRD
- 2006 Jul - Detectors arrive from Japan
- 2006 Sep - Groundbreaking for detector hall
- 2006 Nov - EC assembly complete
- 2006 Jan - Civil construction complete
- 2007 Feb - SciBar assembly complete
- 2007 Mar - MRD assembly complete
- 2007 Mar - Detector hall ready
- 2007 Mar - Cosmic ray data
- 2007 Apr - Detector installation
- 2007 May - Detector commissioning
- **2007 June - Beam data run!**

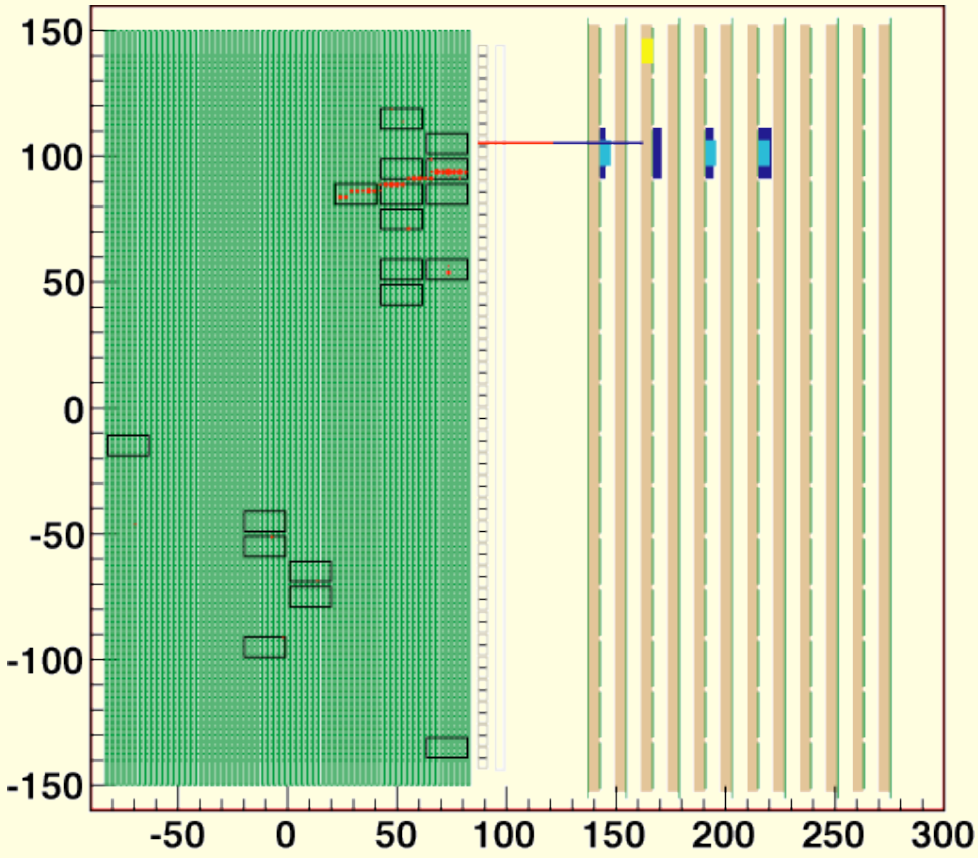
Detector Installation



SciBooNE students worked hard to ensure the success of the installation!

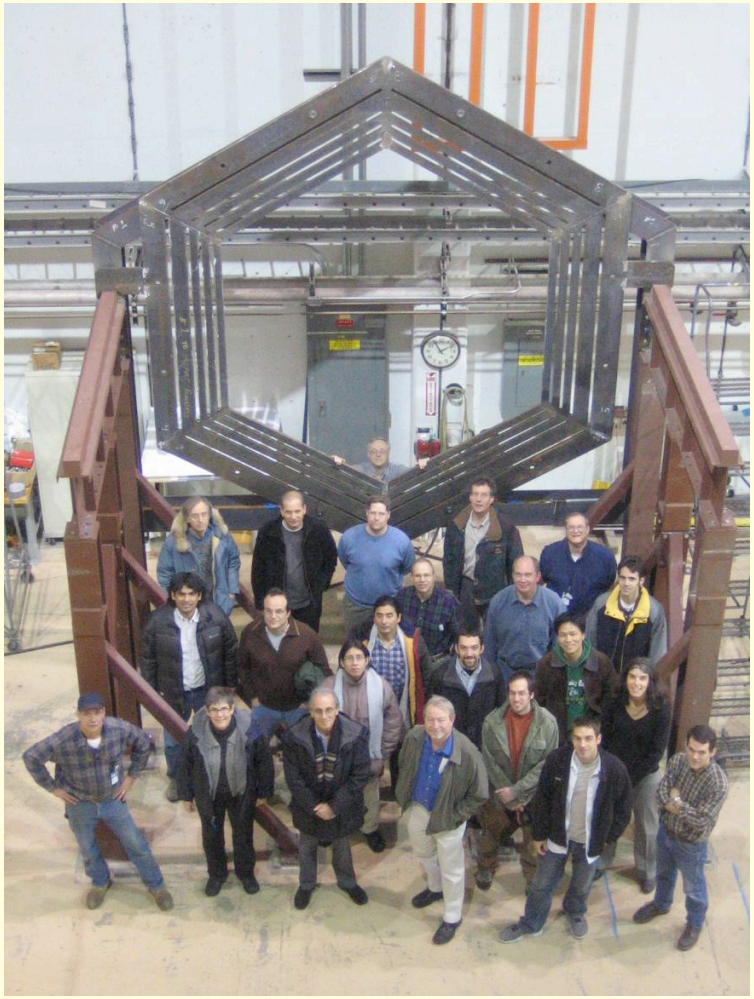
Photo of Yasuhiro Nakajima by Joe Walding

First beam neutrino event



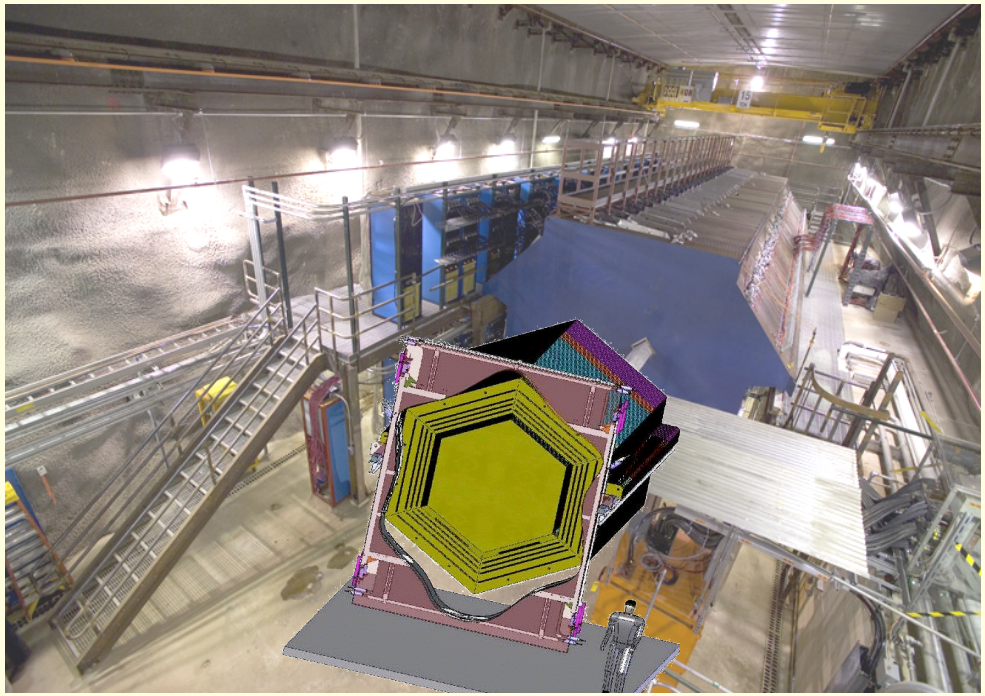
5/28/07

Milestones for MINERνA



- Proposed : December 2003
- PAC approval : April 2004
- CD-1/2/3a : 30March 2007
- August 2007 : CD-3b review scheduled
- Late 2007 – early 2008: Construction of “Tracking Prototype”
  - 20 detector modules
  - Will use to study tolerance stackup, tracking, etc.
- Late 2008: Test beam detector taking data
- 2008-2009: Construction of full detector
- 2010:Installation/commissioning of detector.

MINERνA Run Plan



- 1 “year” = 4.0 x 10^{20} POT taking data in the LE beam configuration with MINOS
- 3 “years” = 12.0 x 10^{20} POT taking data in the ME beam configuration with NOνA

Event Sample:
Assume: 4.**0 x** 10^{20} POT LE and
12.**0 x** 10^{20} POT ME beam

14.5 Million total CC events

Fiducial Volume = 3 tons CH, 0.2t He, 0.15t C, 0.7t Fe and 0.85t Pb
Expected CC event samples:
9.0 M ν events in 3 tons of CH (totally active central detector)
0.6 M ν events in He
0.4 M ν events in C
2.0 M ν events in Fe
2.5 M ν events in Pb

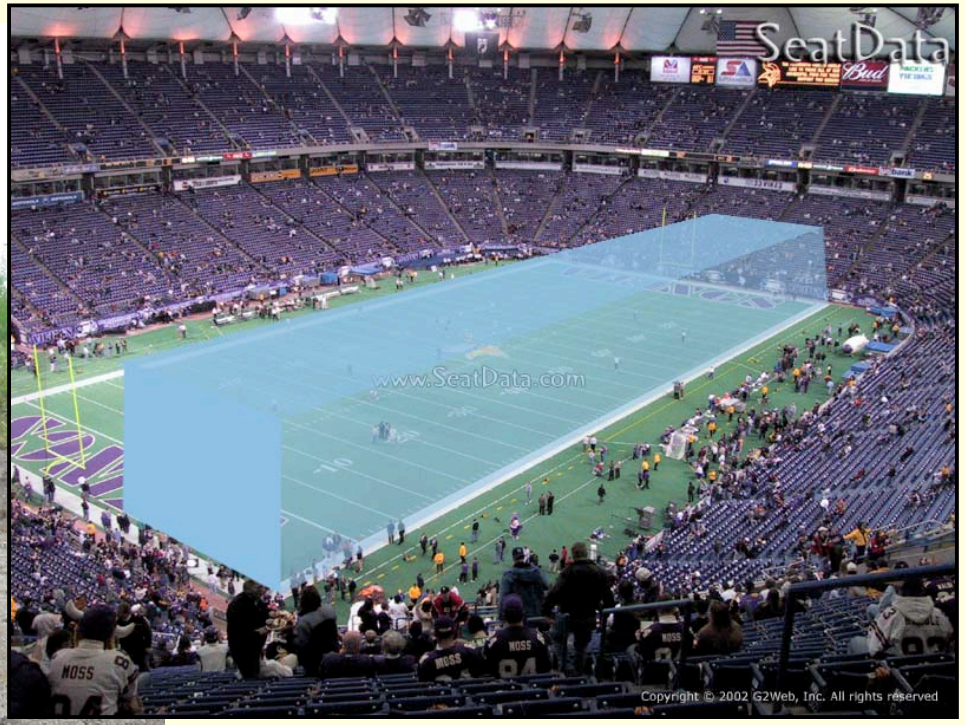
Main CC Physics Topics (Statistics in CH only)

• Quasi-elastic	0.8 M events
• Resonance Production	1.7 M total
• Transition: Resonance to DIS	2.1 M events
• DIS, Structure Funcs. and high-x PDFs	4.3 M DIS events
• Coherent Pion Production	89 K CC / 44 K NC
• Strange and Charm Particle Production	> 240 K fully reconstructed events
• Generalized Parton Distributions	order 10 K events
• Nuclear Effects	He: 0.6 M, C: 0.4 M, Fe: 2.0 M and Pb: 2.5 M

News from NOνA

- **4/05:** PAC recommends Stage I approval for NOνA
- **11/05**: Ray Orback approves DOE CD-0 (Mission Need) for "EvA"
- **2/06**: EvA in President's FY07 budget for $10.3M
- **2/06**: NuSAG report - "The U.S. Should conduct the NOνA experiment at Fermilab"
- **2/06**: Director's Review for CD-1 (Cost, schedule and scope range)
- **4/06**: DOE Lehman Review for CD-1 - "CD-1 Approval is recommended"
- **10/06**: P5 Report - "Proceed with the 20 kt scale NOνA Experiment" ($200M implied)
  - Provides information for the next step on the road to measuring CP violation, e.g. conventional beams vs neutrino factory…
- **2/07**: NOνA in President's FY08 budget for $36M
- 5/02/07 : Office of Science issues CD-1 approval
- **6/07 : Director's Review in preparation for CD-2/3a review**
- 7/07 : DOE CD-2/3a review scheduled

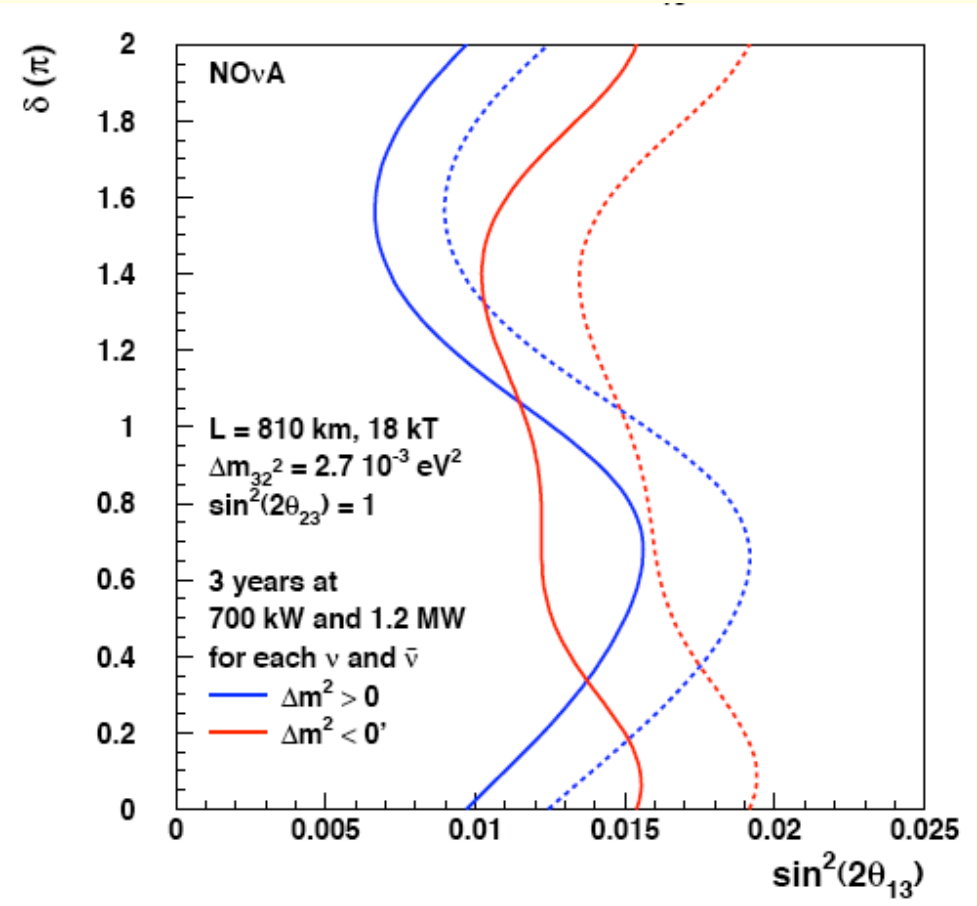
The NOνA Project



- Liquid scintillator in 3.9 cm (W) x 6.6 cm (D) x 15.7 m (L) cells
  - ~20 kton (goal) but TPC is "capped" @ $260 M
  - ~500,000 cells in alternating x-y planes
  - 4 million gallons of liquid scintillator
  - 17,000 km of fiber

Physics with NOνA

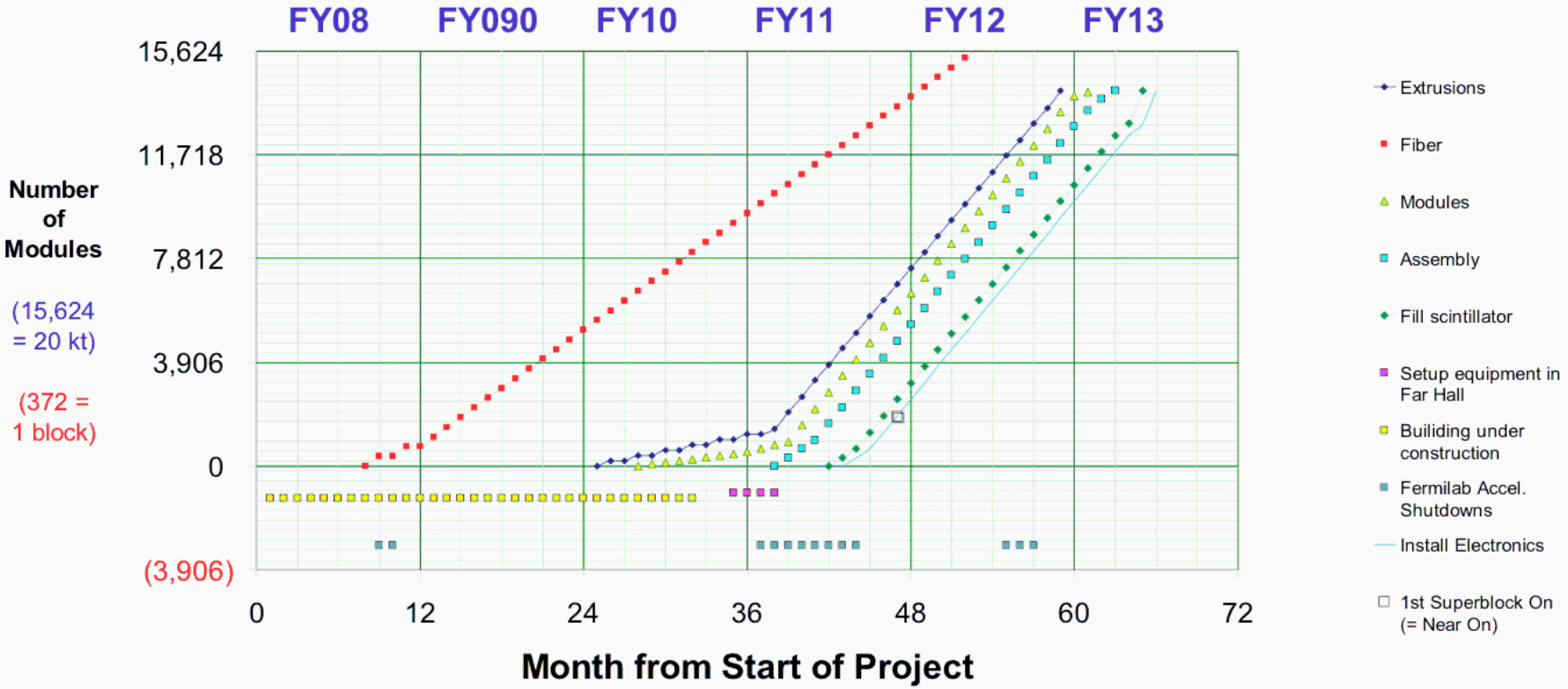
3σ Sensitivity to $\theta_{13} \neq 0$



- Primary Goal :
  - Study of $\nu_\mu \rightarrow \nu_e$ oscillations
    - $\sin^2 2\theta_{13}$
    - the sign of Δm_{32}
    - the CP-violating phase δ
- Level of "success" depends on *NATURE*
  - Current limit on $\sin^2 2\theta_{13}$~0.14 (90% CL)

Schedule

– Critical path is building, then assembly at Ash River



θ_{13} Program

- Phase I (~2009 - ~2013):
  - World wide effort to measure θ_{13}
    - Reactor experiments :
      - Double Chooz and Daya Bay
    - Accelerator long baseline :
      - JPARC to SuperK (T2K) and NOνA
  - Phase I experiments will determine if $\sin^2 2\theta_{13} > 0.05$ very quickly
  - If **$\sin^2 2\theta_{13} > 0.05$** NOνA may be able to determine the mass hierarchy (depends on the value of δ_{CP})
  - If **$0.02 < \sin^2 2\theta_{13} < 0.05$** it will take longer to determine this;
    - determining the mass hierarchy will be difficult and sensitivity to CP is achievable but even more challenging

Future Long Baseline Study (sponsored by BNL/FNAL)

March 2006 - May 2007

arXiv:0705.4396 (May 2007)

Fermilab-0801-AD-E
BNL-77973-2007-IR

Report of the US long baseline neutrino experiment study

V. Barger,[1] M. Bishai,[2] D. Bogert,[3] C. Bromberg,[4] A. Curioni,[5] M. Dierckxsens,[2] M. Diwan,[2] F. Dufour,[6] D. Finley,[3] B. T. Fleming,[5] J. Gallardo,[2] D. Gerstle,[5] J. Heim,[2] P. Huber,[1] H. Jostlein,[3] C. K. Jung,[7] S. Kahn,[2] E. Kearns,[6] H. Kirk,[2] T. Kirk,[8] K. Lande,[9] C. Laughton,[3] W. Y. Lee,[10] K. Lesko,[10] C. Lewis,[11] P. Litchfield,[12] A. K. Mann,[9] A. Marchionni,[3] W. Marciano,[2] D. Marfatia,[13] A. D. Marino,[3] M. Marshak,[12] S. Menary,[14] K. McDonald,[15] M. Messier,[16] W. Pariseau,[17] Z. Parsa,[2] S. Pordes,[3] R. Potenza,[18] R. Rameika,[3] N. Saoulidou,[3] N. Simos,[2] R. Van Berg,[9] B. Viren,[2] W.T. Weng,[2] K. Whisnant,[19] R. Wilson,[20] W. Winter,[21] C. Yanagisawa,[7] F. Yumiceva,[22] E. D. Zimmerman,[8] and R. Zwaska[3]

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[2]*Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
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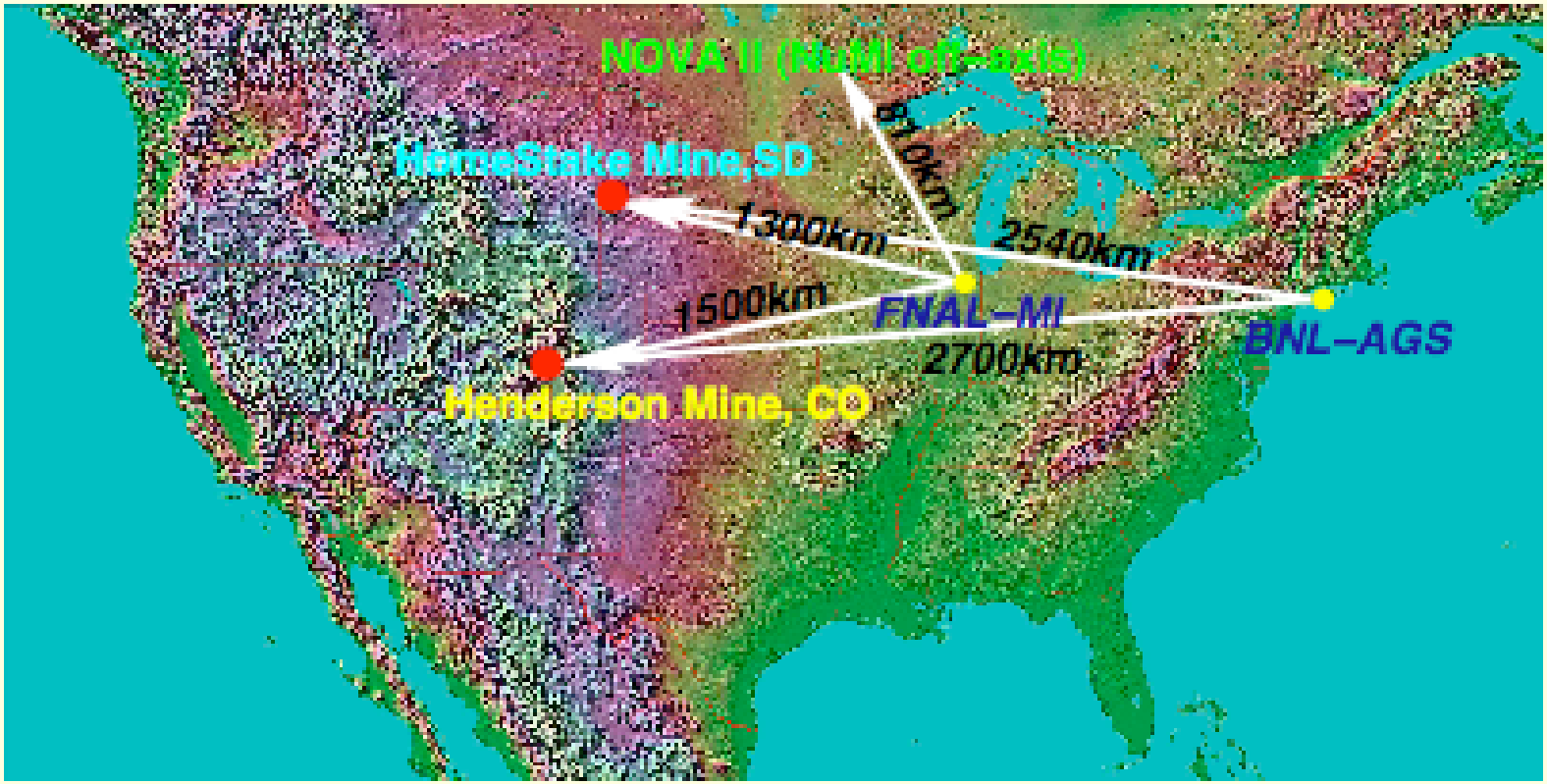
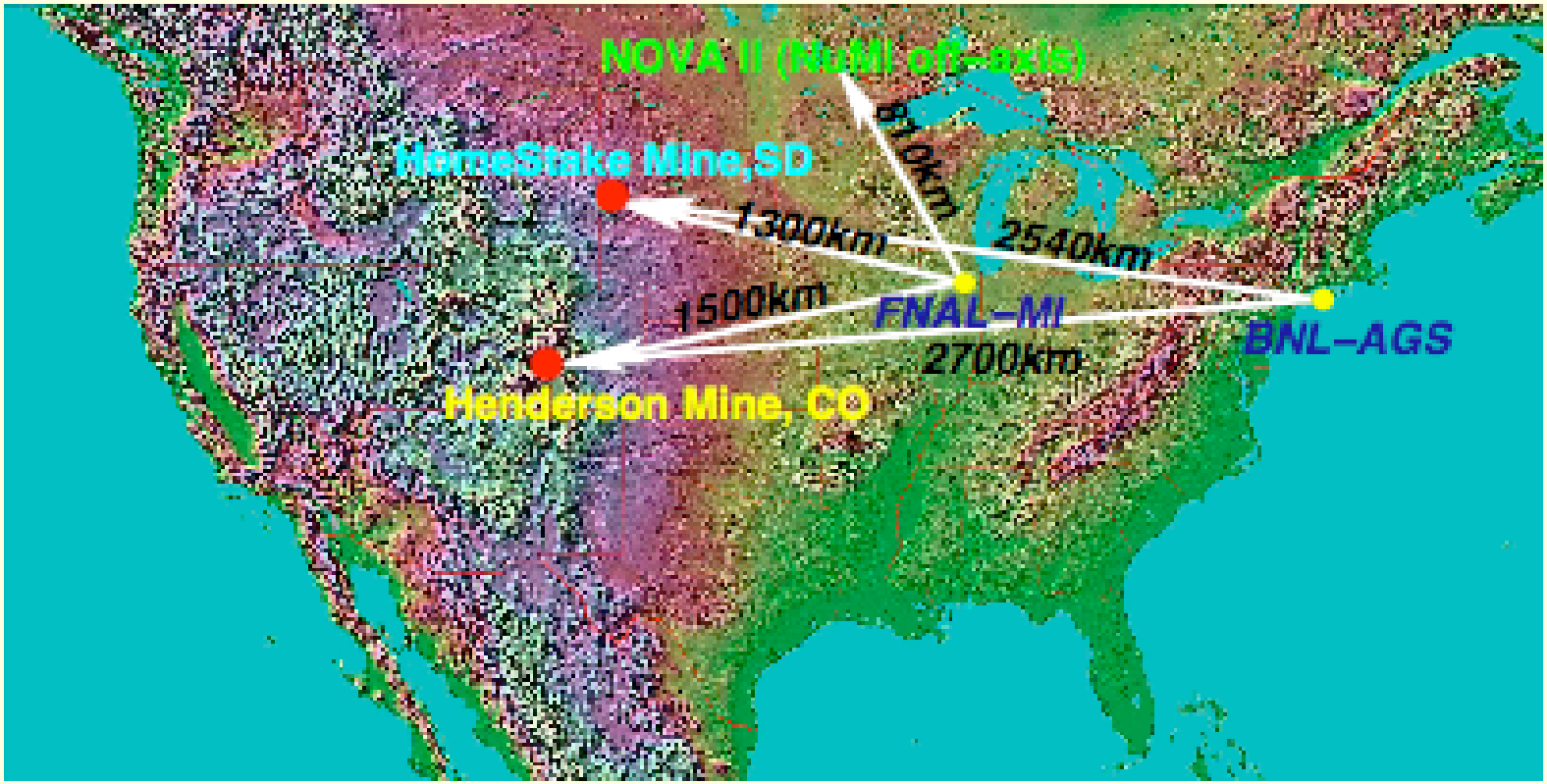
[12]*School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*
[13]*Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA*
[14]*Department of Physics and Astronomy, York University, Toronto, Ontario M3J1P3, Canada*
[15]*Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[16]*Department of Physics, Indiana University, Bloomington, IN 47405, USA*
[17]*Department of Mining Engineering, University of Utah, Salt Lake City, UT 84112, USA*

Special thanks to Milind Diwan, BNL

Future Long Baseline Options

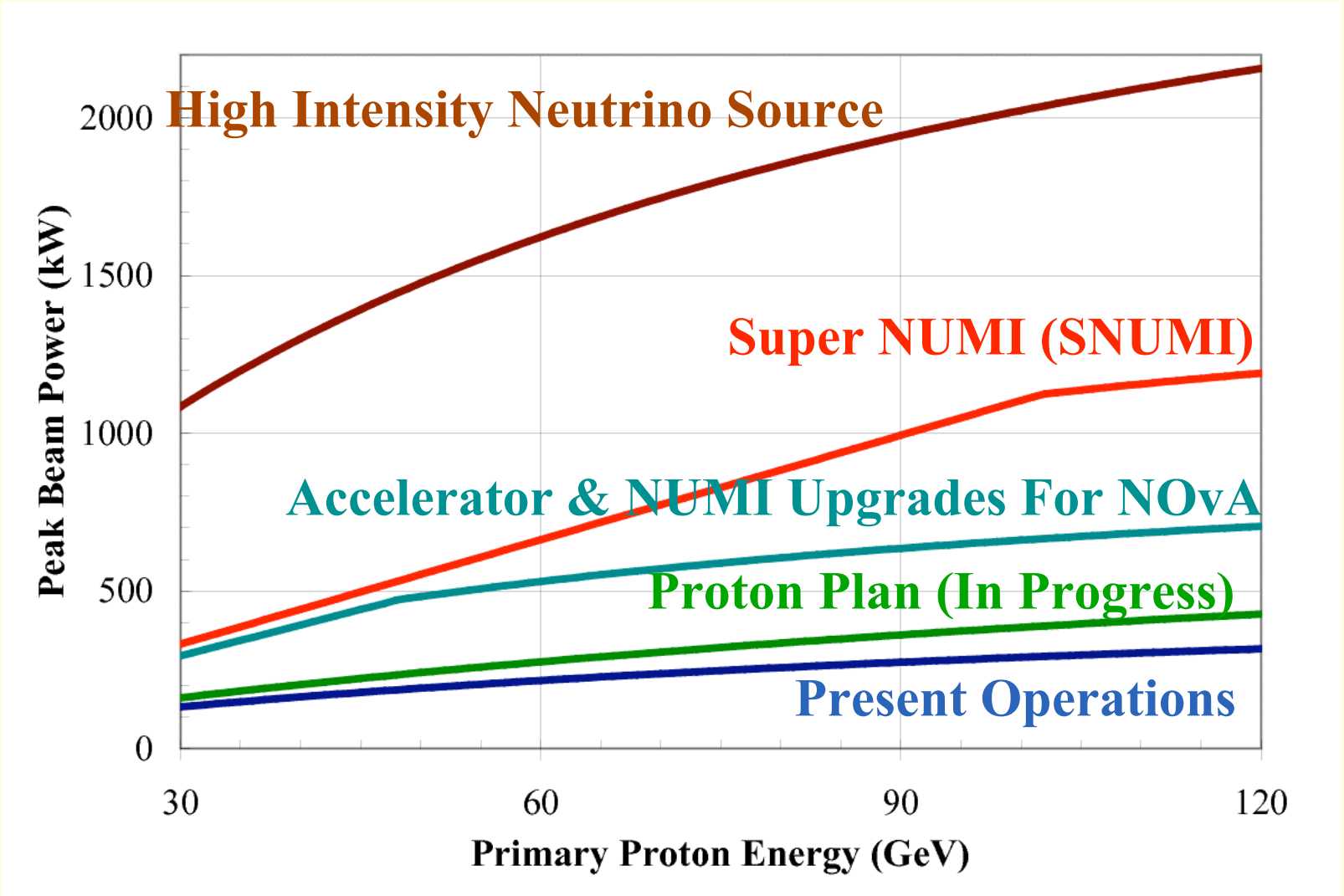


Future Long Baseline Options

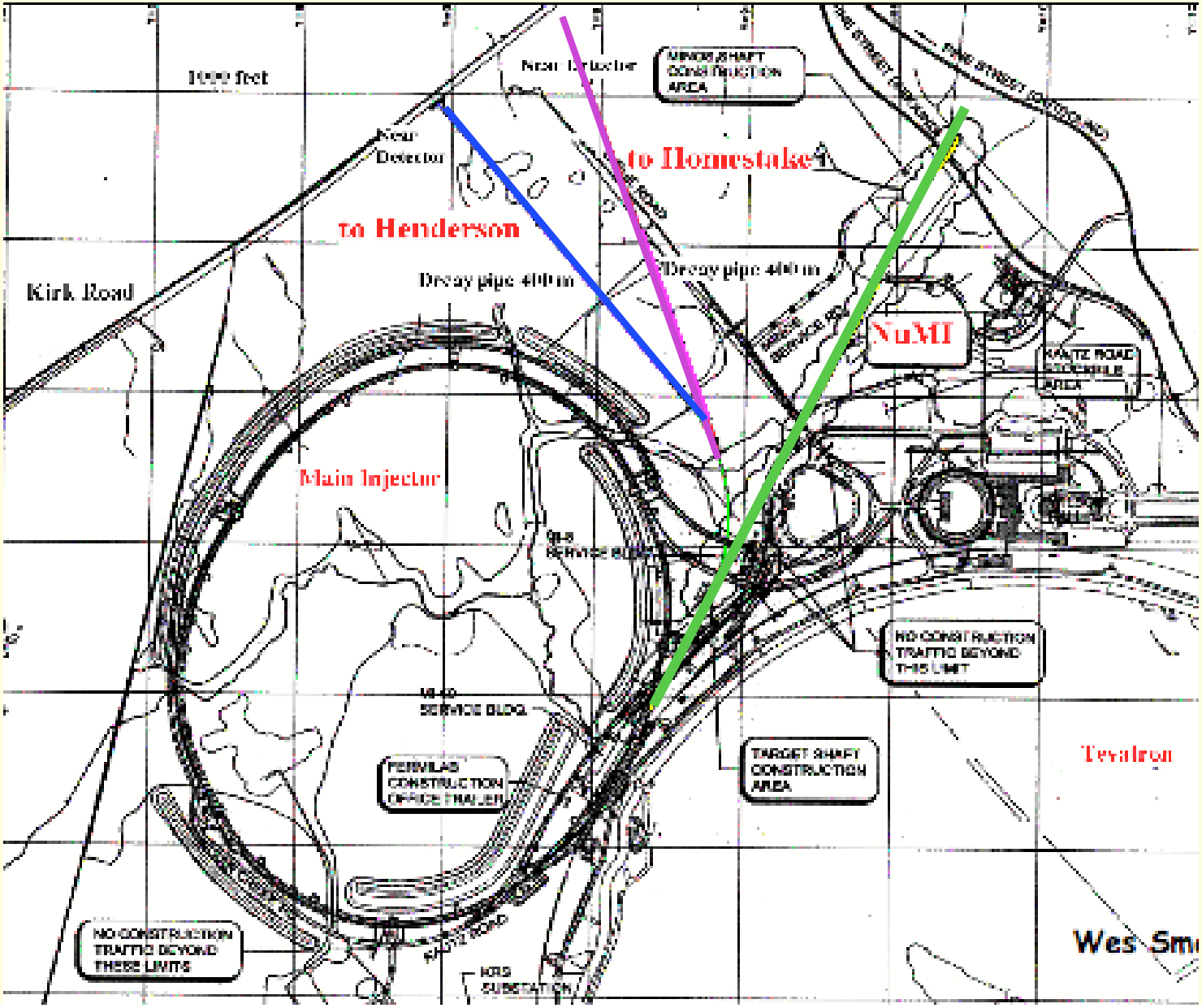


Study focused only on the option of using the Fermilab Accelerator complex.

Options for Proton Power

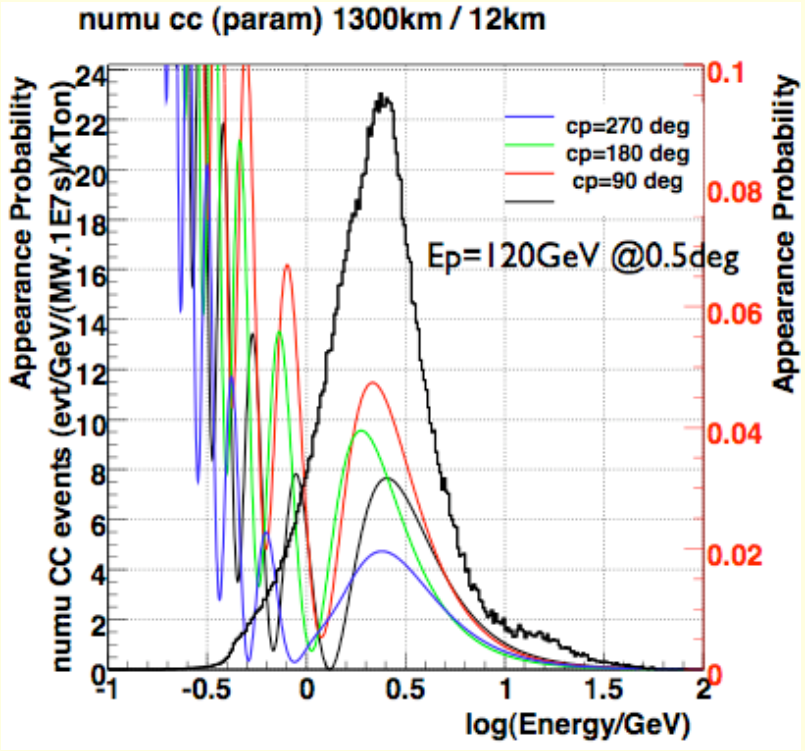


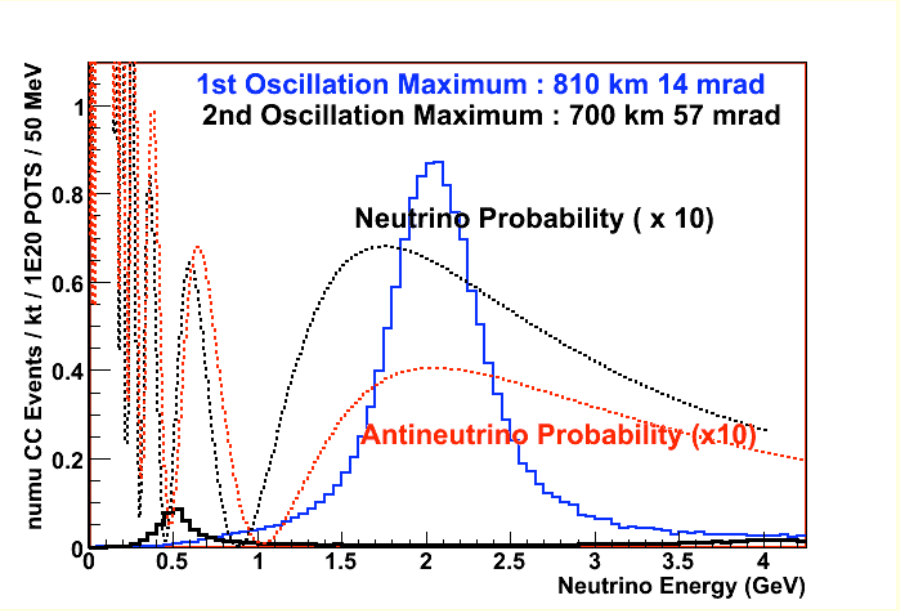
ν beam Options at FNAL



ν beam Options

- NuMI - Off-Axis (narrow band)





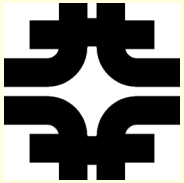
- NEW - Wide Band Beam

Some conclusions of the study

- Two Options for a future program - how to choose will be easier once Phase I experiments present results

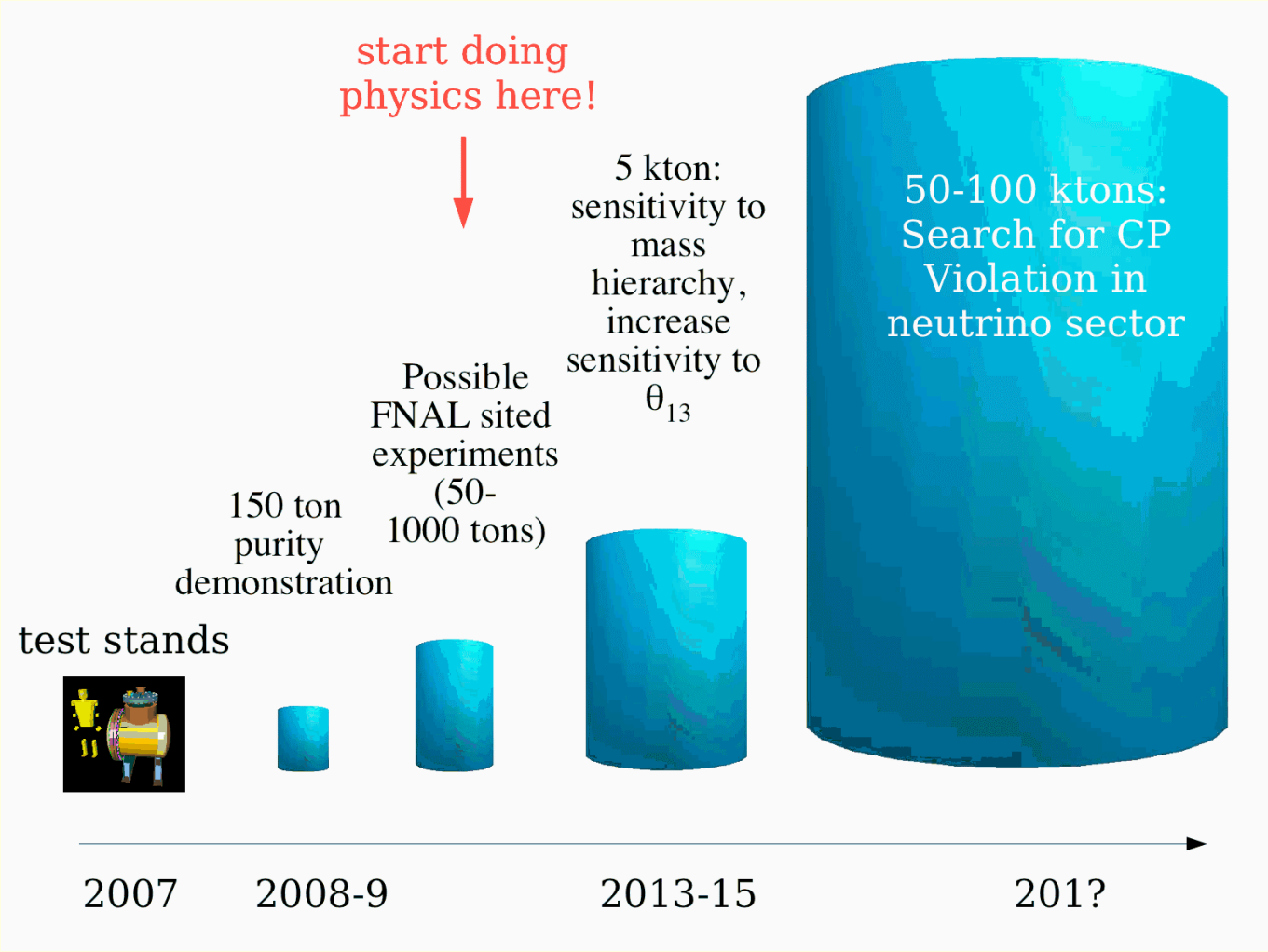
  - **Existing NuMI Off-axis** option is good for
    - $\sin^2 2\theta_{13} \neq 0$ as low as 0.005
    - Mass hierarchy for large "ish" θ_{13}
      - Specific sensitivity depends on protons, mass and running time
    - possible exploration of CP violation in neutrino sector

  - **New WBB at a longer baseline** may be necessary for determining the mass hierarchy for all values of δ_{CP} if $\sin^2 2\theta_{13}$ turns out to be quite small
    - Win with baseline and the Wide band beam which enables one to fit the observed spectrum to the oscillation parameters



- Either option requires
  - Detector masses >> 100kton
  - Megawatt class proton source
- R &D on large scale detectors necessary
  - Water cerenkov
    - Proven, well understood technology
    - Scaling to ~100-300 kton seems feasible
    - Needs to operate underground
  - Liquid argon
    - Potentially high resolution and excellent background rejection
    - Cost and Technical scaling is a challenge
    - Possibly could operate on the surface

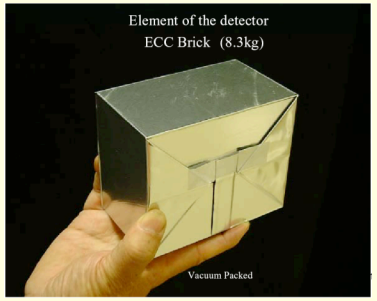
Concept for evolution



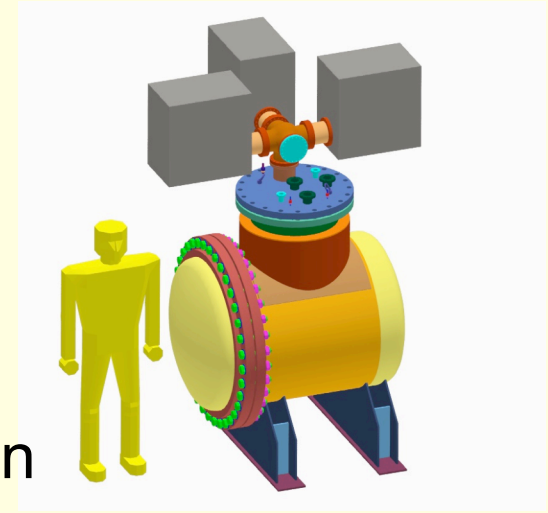
http://www.fnal.gov/directorate/Longrange/Steering_Public/documents.html

B. Fleming
5/31/07

Detector R & D

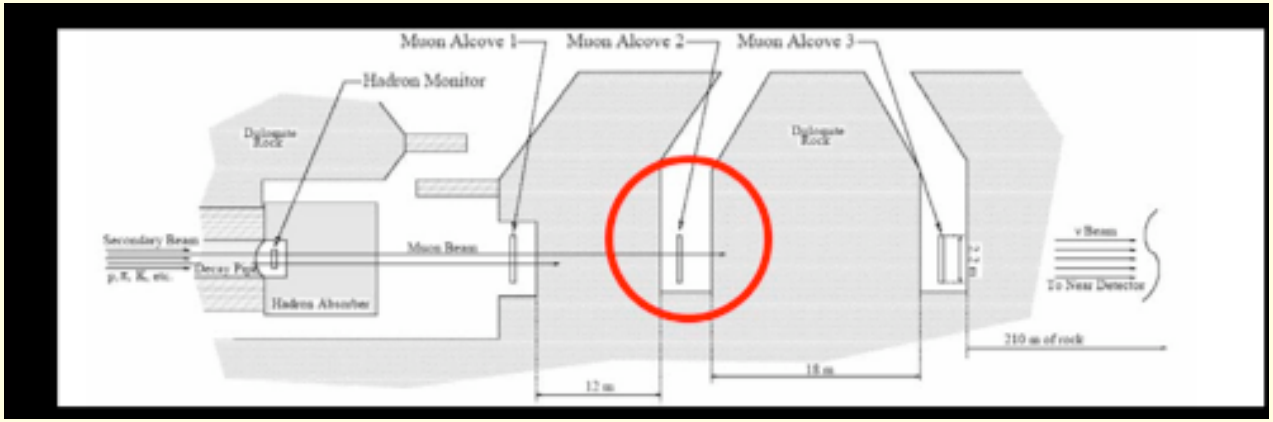


T-952
OPERA emulsion bricks



T-962 mini-LAr TPC

T-968 T2K MUMON



Conclusions & Outlook

- Fermilab neutrino program is active and diverse.
- Operating experiments MINOS and MiniBooNE are producing exciting results and publications.
- SciBooNE has completed installation and is commissioning with neutrino beam
- The MINERνA experiment is on the approval path, and progressing well in R&D and prototyping
- The NOνA project is also progressing through the review process and will hopefully move from R&D to construction before the end of this FY.
- Planning for a θ_{13} Phase II experiment is an important part of our neutrino program
- Our existing facilities are being used to support a variety of R&D test activities for both the Fermilab and the world wide neutrino program.